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THESIS

PACIFIC FLEET SUBMARINE TENDER OPTIMIZATION

by

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June 2013

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PACIFIC FLEET SUBMARINE TENDER OPTIMIZATION

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ABSTRACT

In this thesis, we develop a mixed-integer, linear optimization model to guide the resourcing of submarine maintenance conducted by the U.S. Navy's two submarine tenders in the Fifth and Seventh Fleets. We assume maintenance demands are known over a given planning horizon, e.g., one month. Inputs to the model include travel times and costs for fly-away teams and tenders to move to where the maintenance is needed. Each maintenance demand can be divided into tasks with characteristics such as: whether or not tender presence is required; the estimated total number of worker-days required; the maximum number of workers that can simultaneously work on each task; the types of maintenance workers that can perform the task; and task due dates. The model's output determines the assignment of personnel to meet the demand at minimum cost, including delay penalties. It also guides personnel travel (as a fly-away team or by tender). In addition, the model can be used to accommodate emergent, unscheduled demands by producing an updated schedule that minimizes the impact on an existing schedule. We test our model on small and realistically sized notional examples to demonstrate the input and output of the models, as well as computational run-times.

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LIST OF ACRONYMS AND ABBREVIATIONS

AOR	Area of responsibility
APR	Asia-Pacific region
CIVMAR	Civilian mariner
CNO	Chief of Naval Operations
DoD	Department of Defense
FAT	Fly-away team
MSC	Military Sealift Command
PSOM	Planned Maintenance Scheduling Optimization Model
RSOM	Rescheduling Optimization Model
SSN	Nuclear-powered attack submarine

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I. INTRODUCTION

A. OVERVIEW

In World War I, the Navy began to use submarine tenders extensively as submarines became increasingly important to critical missions. However, after the end of the Cold War, as the Department of Defense (DoD) reduced the size of its operating forces, the total number of nuclear-powered attack submarines (SSNs) reduced from a goal of one hundred in the 1980s to forty three SSNs today [1]. As a result, during the 1990s, the number of tenders reduced from ten to two: the USS Frank Cable and USS Emory S. Land [2].

These tenders currently operate out of the ports of Apra Harbor, Guam and Diego Garcia, respectively, and “furnish maintenance and logistic support for nuclear attack submarines” [3] for the Fifth Fleet area of responsibility (AOR) and Seventh Fleet AOR. These ships are capable of simultaneously mooring up to four submarines alongside the ship to conduct maintenance. Tenders are also capable of traveling at speeds up to twenty knots [4]. The Joint Fleet Maintenance Manual explains that

[t]enders are specially configured to provide intermediate-level maintenance support to deployed and non-deployed forces. They have full intermediate-level repair capability in the hull, mechanical, and electrical repair areas and have extensive battle-damage repair capabilities. Although initially designed to serve one type of customer, they are becoming increasingly able to support both surface ships and submarines. These ships typically provide their support services from relatively secure ports or anchorages, with the tended forces coming to their location. [5]

The island of Guam is centrally located in the Western Pacific Ocean, south of Japan, east of the Philippines, and near routes where submarines and other ships travel. Diego Garcia is an atoll centrally located in the British Indian Ocean Territory approximately one thousand nautical miles south of India. Unlike Guam, Diego Garcia is several days away from submarine operating areas and not along any routes. As a result, the USS Emory S. Land in Diego Garcia does not receive as much maintenance demand as the USS Frank Cable in Guam [6]–[7].

Scheduling these limited resources, both maintenance personnel and tenders, is a complicated job. The scheduling decisions involve prioritizing among competing maintenance demands while considering time-distance constraints and costs. As a result, current planning methods (devised manually by experienced planners based on task priority) may not be optimal in cost or amount of work completed.

B. LEADERSHIP GUIDANCE

1. U.S. President's Guidance

In his latest National Security Strategy, the U.S. President Barack Obama stated that one of the priorities for the U.S. is to increase support for our partner nations and allies in the Asia-Pacific region (APR) [8]. This was reinforced on November 17, 2011, in his speech to the Australian Parliament. The President stated that one of his objectives is to promote security in the region and resolve conflict between emerging powers to ensure trade is not hindered, therefore allowing the U.S. to grow economically by increasing trade with this fast-developing region. The President assured the U.S. allies and partner countries that there will be no cut to the defense budget for the APR [9].

The APR, shown in Figure 1, while ambiguous, is generally considered to consist of the countries of South East Asia to Australia, and the Pacific Islands. The APR accounts for more than a quarter of the U.S. trade, and that percentage is expected to increase. Currently, the region accounts for seven of the top fifteen export countries for U.S. manufacturing and eight of the top fifteen export countries for U.S. agriculture [10]. This region is expected to continue to grow in importance in the future. Tom Donilon, the National Security Advisor for the Obama Administration, in November 2012 stated:

Economically, it's impossible to overstate Asia's importance to the global economy and to our own. Asia accounts for about a quarter of global GDP at market exchange rates, and is expected to grow to nearly 30 percent by 2015. The region is estimated to account for nearly 50 percent of all global growth outside the United States through 2017. The region accounts for 25 percent of U.S. goods and services exports, and 30 percent of our goods and services imports. An estimated 2.4 million Americans now have jobs supported by exports to Asia, and this number is growing. In short, robust U.S. trade and investment in Asia will continue to be critical for our economic recovery and our long-term economic strength [11].

However, during this period of growth and development, this region is also becoming increasingly unstable [10].



Figure 1. Map of the APR and its neighbors. From [10].

The APR has a history of tensions largely founded by histories of war and countries now grasping for vital resources within the region. Examples of this tension include the Korean Peninsula and the surrounding area, which are under a persistent threat from North Korea, which continues to threaten the U.S. and its allies. North Korea seeks to produce or procure nuclear weapons and develop a long-range ballistic missile program extending the range of the country's ability to threaten further neighbors. Meanwhile, China's increasing military strength increases the tension within the region. Japan and China continue to argue over ownership of small unpopulated islands in order to control the resources and waterways nearby. And, China claims ownership of Taiwan, which cannot gain independence due to the threat of war [10].

Further to the west, the President wants to rebalance the focus from Iraq and Afghanistan to the greater Middle East and to strengthen our diplomatic bonds with India [8], another fast-developing country with the capability to provide security to a large region in the Indian Ocean. However, India is continually dealing with its own tensions with Pakistan. Both of these countries are equipped with nuclear weapons and continue to develop the capability for long-range nuclear missiles to strike deeper into each other [12]. Meanwhile, the U.S. also seeks to preserve the volume of supplies that move through the Persian Gulf which is constantly under the threat of closure through the Strait of Hormuz by Iran. This is a key waterway for transporting the majority of the world's oil. Like North Korea, Iran also seeks to produce or procure nuclear weapons. These threats stir fear in neighboring countries which results in greater instability.

2. Secretary of Defense's Guidance

Operating under the President's guidance, the Secretary of Defense published his Defense Strategic Guidance emphasizing the need to shift DoD forces from the wars in Iraq and Afghanistan and to reduce the number of DoD forces in Europe. This shift will increase stability in the APR and Indian Ocean, counter extremism in the Middle East, and provide security to the Persian Gulf region. All of these areas are connected to the future growth of the U.S. economy. The security provided by our military working with our partners and allies will promote “peace, stability, the free flow of commerce, and of U.S. influence” [13].

Simultaneously, the U.S. is currently facing budget shortfalls which will reduce the resources available for completing these goals. As the nation completes the combat operations in Iraq and Afghanistan, it naturally will scale down the size and funding for the DoD. The Defense Budget Priorities and Choices report from January 2012 [14] projects a reduction of 22% from the DoD's 2010's budget level to occur from 2013 to 2018. Meanwhile, the DoD will support the President's strategic guidance by rebalancing the forces to increase the focus on the APR and the Middle East.

3. Maritime Strategy

Similarly, the Chief of Naval Operations (CNO), the Commandant of the U.S. Marine Corps, and the Commandant of the U.S. Coast Guard collaboratively released the maritime strategy, *A Cooperative Strategy for 21st Century Seapower*, which emphasizes the importance of and gives guidance for these services' focus to be on dominating the sea environment. Since global population will continue to increase over the next century, the demand for global resources will also increase. Population growth is predicted to occur most rapidly near the oceans and seas. This will place stress on the world's waterways to deliver the necessary resources and will increase the need for humanitarian assistance and conflict avoidance. For these reasons, the missions conducted by the U.S. Department of the Navy will continue to increase in demand over the next century [15].

4. Chief of Naval Operation's Guidance

In line with the guidance given, the CNO gives three tenets in his Navigation Plan for 2013-2017: *Warfighting First*, *Operate Forward*, and *Be Ready*. In each of these tenets, the CNO's guidance is conveyed to the subordinate commanders [16].

The first tenet, *Warfighting First*, addresses the tensions in the Arabian Gulf and the support of the U.S. allies in the APR. In one of the key points of this tenet, the CNO stresses the importance to “continue to dominate the undersea environment.” The goal of the second tenet, *Operate Forward*, is to posture forces in known areas of instability in order to “deter, influence, and win.” Again, the regions that the CNO addresses are the Middle East and the APR. The guidance specifically states that the Navy will need to sustain port facilities that are most important for resupply and maintenance. Some of the locations that are specifically listed are the ports in Diego Garcia, Guam, Bahrain, Singapore, Japan, and the Republic of Korea. Further, to operate forward longer, the CNO seeks to explore options for deploying rotational crews and using the Navy's Civilian Mariners (CIVMARs) for more roles. In the final tenet, *Be Ready*, the CNO states that within the budget guidelines the Navy will seek to maximize readiness by “establishing a sustainable deployment schedule that affords sufficient time for maintenance and training” [16].

C. SUBMARINE MISSIONS

The importance of the regions incorporated in the U.S. Navy's Fifth and Seventh Fleet AORs is clear, and the deployed submarines play a key role in the aforementioned plans. The U.S. Navy currently has forty-six attack submarines, four guided-missile submarines, and fourteen ballistic-missile submarines in service [17]. These submarines support the leadership's guidance by conducting their missions, undetected in forward deployed and sensitive areas, a capability which other ships do not possess. Submarines can operate independently or as a part of a larger task force. The knowledge that these submarines are deployed can deter adversaries from hostile acts. Submarines conduct several missions, including collection of information through surveillance, reconnaissance, or through the insertion of special operations forces. Further, submarines can also defeat an adversary through anti-surface warfare, anti-submarine warfare, missile-strike missions using Tomahawk cruise missiles, or through mine warfare. In order for the submarines to conduct these missions successfully, they must receive adequate maintenance support [17]–[18].

D. FORWARD-STATIONED SUBMARINES

There are currently three SSNs home-ported at Guam. From this Navy base they are stationed geographically closer to the APR than any other submarines. This allows them to stay deployed for longer periods of time and respond more quickly to a crisis, which contributes to the increased U.S. support for its allies in the APR. Meeting the U.S. leaderships' guidance, the Deputy Secretary of Defense announced in April 2013 that a fourth SSN is to be home-ported at Guam starting in fiscal-year 2015 [19].

The submarine tender at Guam, the USS Frank Cable, is stressed to support the three SSNs currently home-ported at Guam, in addition to being prepared to conduct voyage repair missions for any of the submarines deployed to the Western Pacific. To this end, two options considered by the navy include expanding the shore facility (that can work in parallel to the submarine tender), and/or home-porting the second tender, the USS Emory S. Land, closer to Guam to fulfill added maintenance demand. The latter

option increases the risk for the submarines operating in the Fifth Fleet AOR due to the increased travel time for a tender to respond to voyage repair maintenance there [6].

E. MILITARY SEALIFT COMMAND

The two tenders are currently assigned to the U.S. Navy's Military Sealift Command (MSC). MSC, established in the years after World War II, integrated the work of four logistic agencies in order to have a single sea logistics command that responds better to the entire DoD's ocean transportation logistics needs [20]. Since the inception of MSC, the number of these non-combatant ships assigned has varied but the number of missions and specialized types of ships within the organization continues to grow. Today, MSC consists of 116 ships, with an additional fifty inactive ships. MSC ships conduct missions through the use of approximately 8,000 CIVMARs, Active and Reserve Component naval personnel, and civil service personnel. MSC is further augmented by the use of military contractors [21].

Prior to being transferred to MSC, submarine tenders were assigned to the operational forces. The USS Emory S. Land was transferred to MSC in 2008 and the USS Frank Cable was transferred shortly after, in 2010. The transfer was made in order to save costs and increase productivity by reducing the number of personnel assigned to the tenders, and allowed the Navy to reallocate the sailors previously assigned to the tenders to other U.S. Navy combatant surface ships [22]. In order to achieve further savings, the "hybrid crew design" was implemented aboard the tenders. Under this design, these ships operate under the command of a U.S. Navy captain, crewed by the CIVMARs, and have navy sailors on board to conduct the maintenance missions. The balance of work between these two groups is divided such that "[t]he CIVMARs are responsible for the ship's deck department, navigation, engineering plant, galley and steward services, and also have primary responsibility for communications and ship supply functions. The uniformed personnel assigned as crew members operate the shipboard information systems, maintain defensive weapons systems and coordinate supply functions with CIVMARs [23]." Previously, the concept of a hybrid crew was only seen aboard the two MSC command ships, and is still rare within MSC and the

Navy. The savings in manpower are significant. “[The USS Emory S.] Land’s crew size changed from 581 military in 2007 to a combined crew of 170 military and 157 CIVMARs in 2008. [The USS Frank] Cable’s crew size changed from 599 military in 2009 to a combined crew of 170 military and 157 CIVMARs in 2010” [24].

F. MAINTENANCE TYPES, FACILITIES, AND RESTRICTIONS

Maintenance is defined in the Naval Doctrine Publication 4, Naval Logistics, as “[t]hose actions necessary to preserve, repair, and ensure continued operation and effectiveness of weapon systems and components” [25]. Maintenance is categorized into one of three types based on complexity and the tools required to perform it. The first type of maintenance is that which can be performed by the ship's crew and is called organizational-level maintenance. The second type, intermediate maintenance, requires support from outside of the ship’s organic crew. Intermediate maintenance can be conducted at nearly any forward operating area, depending on the need of the ship, by transporting the personnel, equipment, and/or facilities required to conduct this maintenance. The third type, depot level maintenance, requires a shipyard or ship repair facility and can involve dry-docking the ship in order to complete these maintenance tasks [25].

Additionally, all maintenance is either preventive or corrective. Preventive maintenance is conducted on a predetermined schedule, and corrective maintenance is unplanned. Depending on the severity of the corrective maintenance task, it can be deferred until the ship's next scheduled maintenance availability period or it may require a voyage repair [25]. Voyage repair maintenance is defined as maintenance which, if not corrected, prevents a ship from completing its intended missions. This type of maintenance involves only the repair of essential mission equipment to return a ship back to safe operating conditions [5], [25].

Priority levels are assigned to maintenance tasks to distinguish importance. These correspond to numbers one through four and aid decision making to determine when the maintenance will be conducted. A priority value of one corresponds to a voyage repair mission and must be complete. Further, priority two corresponds to an “urgent repair,”

priority three is a “routine repair,” and priority four is “desirable ship work.” All maintenance except that deemed priority one can be deferred to the next maintenance availability [5].

All U.S. submarines are constrained by U.S. Code, Title X section 7310 to conduct their maintenance in the U.S. or Guam [26]. However, there are two exceptions: Voyage repair maintenance and maintenance conducted by the submarine tenders [5], [26].

The Joint Fleet Maintenance Manual Volume III, Deployed Maintenance, gives policies, restrictions, and guidance for deployed ships requiring or conducting maintenance in the Fifth Fleet, Sixth Fleet, and Seventh Fleet AORs. Further, it lists some of the common maintenance facilities and their capabilities in each of these AORs.

Submarines are restricted from receiving maintenance support from contracted foreign nationals due to the sensitivity of these ships. The Ship Repair Facility Japan Regional Maintenance Centers, in Yokosuka, Japan and Sasebo, Japan are exceptions when they use Japanese National Master Labor Contract personnel. However, these facilities are further restricted from performing nuclear work and may require additional maintenance workers to complete the maintenance. In addition, these repair facilities require justification for use due to the U.S. Code Title X restrictions. Therefore, the majority of the deployed submarine maintenance comes from the tenders [5].

The Joint Fleet Maintenance Manual also specifies that fly-away teams (FATs) will be used to correct a maintenance deficiency for any ship that is not collocated with the tender. These FATs offer a quick response and highly mobile group of personnel to be able to meet the ship at a foreign port to conduct voyage repair maintenance. However, a tender is required to be collocated with the submarine to conduct certain maintenance, such as on the nuclear propulsion plant or its related equipment [5], [27].

It is estimated that a quarter to a third of the SSN maintenance conducted by the USS Frank Cable at Guam is preventive whereas the rest is corrective [27]. Likewise, the USS Emory S. Land predominantly conducts corrective maintenance. Planned maintenance requests should be submitted at a minimum of forty days in advance in order for the tenders to have sufficient time to create a work schedule, and order parts and supplies necessary for the maintenance [5]. These maintenance requests are analyzed by the tenders in order to diagnose the problems. Based on the analysis, early estimates

about how to best resource and conduct this maintenance are determined. However, voyage repair corrective maintenance tasks are a particular challenge for maintenance scheduling since, by their nature, they are generally known only a few days in advance. Further, the submarine's commander has the authority to decide whether the severity of maintenance requires the submarine to redeploy early [27]–[28].

G. KEY COMMANDERS FOR SUBMARINE MAINTENANCE IN FIFTH AND SEVENTH FLEETS

The Commander, Submarine Force U.S. Pacific Fleet is in charge of thirty-seven submarines, plus the three home-ported at Guam, the two tenders, and other ships [29]. Due to the limited maintenance capacity of the tenders, no submarine is deployed to the Fifth or Seventh Fleet AORs with known maintenance requirements.

The Commander, Submarine Group Seven is responsible for all submarines assigned to the Fifth and Seventh Fleet AORs. This Commander is also designated Commander of Task Force 54 and 74. These designations give this commander the responsibility for coordinating and executing submarine maintenance requirement for all submarines deployed to the Fifth and Seventh Fleets. Further, the two submarine tenders are also under his operational control. The Commander is responsible for screening all work, from both surface ships and submarines, assigned to the tenders. Likewise, the Commander Submarine Squadron 15, who is in charge of the three submarines home-ported at Guam, also screens work packages brokered to the tenders. As a result of the high demand for submarine maintenance, particularly the three SSNs belonging to that squadron, and the limited capacity of the tenders, surface ship work requests are largely rejected [5], [30].

H. THESIS STUDY

We have developed a software tool that optimizes the maintenance resource allocation of tenders and workers to meet demand over a given time horizon. We describe the tool's underlying mathematical models in Chapter II, and its use on notional scenarios in Chapter III. The tool can assist planners to develop a resourcing schedule for submarine maintenance in the Fifth and Seventh Fleet AORs.

II. MODEL DEVELOPMENT

A. LITERATURE REVIEW

1. Optimization Scheduling Problems

In [31], the author states the purpose of scheduling is to “allocate resources to tasks over given time periods” in order to optimize an objective. He classifies these problems into two types, deterministic and stochastic. In a deterministic model, all of the tasks and task data (release date, due date, and amount of work) are known in advance at the time of optimizing the schedule. On the other hand, in stochastic models only the distribution of release dates, due dates, and amount of work associated with tasks are known. The models we develop in Section B are deterministic since we assume that all planned task information is known. Unplanned tasks are accommodated as they become known, rather than via stochastic optimization.

We highlight the basic types of scheduling models from [31]. The first type, parallel machine models, allows incoming tasks to be processed by an available machine until completed. The machines can be either identical, have different processing speeds in general, or have different processing speeds based on what task it is assigned to complete. Next, flow-shop models require each task to be processed on the same sequence of machines or types of machines. In job-shop models each task has a unique sequence of machines or types of machines in which it needs to be processed. Finally, open-shop models require a task to be processed on each type of machine, but the sequence of machine types does not matter. In our problem, we assume that all workers conduct their work at the same rate, as in the case of identical machines in parallel.

Several model characteristics and objective functions also are described in [31]. In our problem, we incorporate the characteristics of preemption, in which we are allowed to “interrupt the processing of a job,” and machine eligibility restrictions, where not all workers are suitable to work on every task. Our objective function combines the ideas of minimizing the “total weighted completion time,” and the “weighted number of tardy jobs.”

In [32], the authors establish the idea of optimization “with persistence,” which we also employ in this research. The idea is to discourage modifications to an existing plan to preclude a new solution that is “mathematically optimal and technically implementable but managerially impractical.” Instead, penalties are assigned to discourage large changes to the existing plan.

2. Military Applications of Optimization Scheduling Problems

There are numerous military applications of optimization scheduling problems. In [33], the authors model a two-week berthing plan for submarines in port at a submarine base. Submarines, each requiring different demands in port on various days, are scheduled to be berthed in various port locations to meet these demands while minimizing the amount of submarine movement within the port. Similar to our problem, this example also accounts for whether the submarine tender is present. Submarines may request tender-side berthing for maintenance or for other tender-specific tasks, e.g., nuclear testing. The model also uses optimization with persistence to update the schedule as new demands arrive.

In [34], the authors create a ship deployment schedule which maximizes the use of naval humanitarian assistance resources. The model develops a scheduling plan for a single ship which maximizes the amount and type of humanitarian missions conducted over a period of time while penalizing for ship movements, port stays, and fuel consumed. This problem is similar to our problem in many aspects: The resources which are allocated are humanitarian teams which are transported by ship, and the ship can conduct several simultaneous humanitarian missions by leaving assistance teams at various port locations while they conduct their missions. This model also accounts for mission precedence and seeks to prioritize the most important missions.

In [35], the authors create a model to optimize the use of the navy's Combat Logistics Force ships to resupply groups of deployed navy combatant ships. This model creates a schedule for each of these logistics ships to determine when and where they supply fuel and other commodities to the combatant ships, over a given period of time. Their objective is to minimize penalties associated with reduced mission capabilities of

the combatant ships. Penalty values stem from policy decisions associated with predetermined levels of commodities.

B. SUBMARINE TENDER SCHEDULING MODELS

We develop two mixed-integer optimization models for the problem of resourcing deployed submarine maintenance. The first model uses the estimated and/or planned (i.e., known) maintenance demands over a predetermined time horizon, e.g., thirty to forty days. We call this model “Planned Maintenance Scheduling Optimization Model” (PSOM). The second “Rescheduling Optimization Model,” (RSOM) “adjusts” the results from an existing model (PSOM or RSOM) output each time there is significant change in the maintenance demand.

1. PSOM Specifications

PSOM seeks to optimize the resourcing decisions of conducting submarine maintenance over the specified time horizon. It minimizes “penalty points” involving actual costs of different activities and delays in performing maintenance. PSOM analyzes the problem holistically in order to determine how to best assign resources to meet known maintenance demands. The resources that we consider for the problem are the type and quantity of maintenance personnel and the two submarine tenders.

The types of maintenance tasks for a submarine are numerous. The tasks may have different requirements from one submarine to the next due to differences between submarines. These differences occur as each submarine receives a unique combination of modifications to conduct different missions, and may occur within the same class of submarine. Instead of trying to capture each of these specifics, we model the most important characteristics of each task: (a) the type or types of workers who can perform the task; (b) the number of worker-days, i.e., the number of days a hypothetical single worker would require to complete the task; (c) the maximum number of workers that can be assigned simultaneously to each task on a given day (this characteristic can be due to physical space limitation, or to the fact that further division of labor may be infeasible); (d) the day the task must be complete; and (e) whether or not a tender is required to be present to conduct the maintenance, which is the case whenever a task is nuclear in nature.

Maintenance tasks must be decomposed in such a way that every task that requires two different types of maintenance personnel must be split into two tasks, one for each type. For example, if a task requires both mechanics and electricians, then the original task would be replaced by two tasks, one for the electricians and one for the mechanics. However, if a task can be completed by either mechanics or electricians, then it is still considered a single task. We also assume the location and times when planned submarine maintenance is required is a given input determined by the planners. There are many factors that determine when and where a submarine maintenance will occur. These have to do with the security of each port, disruption to the submarine's overall mission, and resource requirements to conduct the maintenance. We assume that tenders and/or FATs must travel to these locations to perform the maintenance.

2. PSOM Formulation

The mathematical formulation of PSOM follows:

Indices, sets, and parameters [units, if applicable]:

A : set of maintenance tasks, for $a \in A$

D : set of days in the time horizon for study, for $d \in D = \{1, 2, 3, 4, \dots\}$

M : set of methods for travel for maintenance personnel, for $m \in M = \{\text{flight, tender}\}$

P : set of ports where maintenance can be performed, for $p, p' \in P$

R : set of maintenance personnel types, for $r \in R$, e.g. $R = \{\text{electrical, sheet metal, machine repair, diving, nuclear}\}$

T : set of tenders, for $t \in T = \{\text{USS Frank Cable, USS Emory S. Land}\}$

D_a : subset of days available to complete task a

p_a : port associated with task a

$D_{p,p'}$: subset of days when flying from p to p' is possible

$A^T \subset A$: subset of tasks where a tender is required to be present in order to perform work on the task

R_a : subset of maintenance personnel types capable of completing task a

$n_{p,r}^0$: the number of maintenance workers of type r at initially at port p [workers]

d_a^{First}, d_a^{Last} : first and last days available to work on task a , respectively [day]

wd_a : total work required to complete task a [workers]

wub_a : maximum number of workers that can work simultaneously on task a [workers]

$travel_{m,p,p'}$: travel time required to move maintenance personnel from port p to p' by travel method m [days]

$c_{m,p,p'}^T$: penalty to transport personnel from port p to p' by travel method m [penalty units/worker]

c_p^D : daily penalty points for each maintenance worker at port location p [penalty units/worker]

$c_p^{D\text{Diff}}$: difference in daily penalty points for each maintenance worker at port location p if assigned to a colocated tender [penalty units/worker]

c_a^M : daily penalty points for delayed maintenance for task a [penalty units/worker-day]

c_a^{Last} : one-time penalty points for unmet maintenance for task a after day d_a^{Last} [penalty units]

$c_tender_{p,p'}^T$: penalty points for a tender to travel from port p to p' [penalty units/tender]

$c_tender_p^D$: daily penalty points of a tender at port location p [penalty units/tender]

$tender_{p,t}^0$: 1 if p is the initial location of tender t , 0 otherwise

$beds_t$: the space available aboard tender t for maintenance personnel to travel or provide in-port lodging.

Decision Variables [units]:

$W_{d,p,r}$: number of maintenance personnel of type r available in port p on day d [workers]

$X_{d,m,p,p',r}$: number of maintenance personnel r moving from port p to p' on day d by method m [workers]

$TP_{d,p,r}$: number of maintenance personnel of type r residing aboard a tender at port p on day d [workers]

$U_{a,d,p}$: work remaining to complete task a on day d at port p [workers]

$Y_{a,d,p,r}$: number of maintenance personnel of type r assigned to maintenance task a on day d at port p [workers]

$W_{d,p,t}^T$: 1 if tender t is available in port p on day d , and 0 otherwise

$X_{d,p,p',t}^T$: 1 if tender t starts moving from port p to p' on day d , and 0 otherwise

O_a : 1 if task a is incomplete at the beginning of day $d_a^{Last} + 1$, and 0 otherwise

Formulation:

$$\begin{aligned} \min_{O, TP, U, W, W^T, X, X^T, Y} \quad & \sum_{a,d|d \in D_a} c_a^M U_{a,d,p_a} + \sum_a c_a^{Last} O_a + \sum_{d,m,p,p',r} c_{m,p,p'}^T X_{d,m,p,p',r} + \sum_{d,p,r} c_p^D W_{d,p,r} \\ & - \sum_{d,p,r} c_p^{Diff} TP_{d,p,r} + \sum_{d,p,p',t} c_tender_{p,p'}^T X_{d,p,p',t}^T + \sum_{d,p,t} c_tender_p^D W_{d,p,t}^T \end{aligned} \quad (1)$$

Subject to:

$$W_{d,p,r} = W_{d-1,p,r} + \sum_{m,p'|p' \neq p} X_{d-travel_{m,p',p},m,p',p,r} - \sum_{m,p'|p' \neq p} X_{d,m,p,p',r} \quad \forall d < |D|, p, r \quad (2)$$

$$W_{d,p,t}^T = W_{d-1,p,t}^T + \sum_{p'|p' \neq p} X_{d-travel_{tender,p',p},p',p,t}^T - \sum_{p'|p' \neq p} X_{d,p,p',t}^T \quad \forall d < |D|, p, t \quad (3)$$

$$\sum_{a|r \in R_a, p_a=p} Y_{a,d,p_a,r} \leq W_{d,p,r} \quad \forall d, p, r \quad (4)$$

$$U_{a,d_a^{First},p_a} = wd_a - \sum_{r \in R_a} Y_{a,d_a^{First},p_a,r} \quad \forall a \quad (5)$$

$$U_{a,d,p_a} = U_{a,d-1,p_a} - \sum_{r \in R_a} Y_{a,d,p_a,r} \quad \forall a, d \mid d \in D_a \quad (6)$$

$$\sum_r X_{d,tender,p,p',r} \leq \sum_t beds_t X_{d,p,p',t}^T \quad \forall d, p, p' \mid p \neq p' \quad (7)$$

$$\sum_{m,p'|p' \neq p} X_{1,m,p,p',r} + W_{1,p,r} = n_{p,r}^0 \quad \forall p, r \quad (8)$$

$$\sum_{p'|p' \neq p} X_{1,p,p',t}^T + W_{1,p,t}^T = tender_{p,t}^0 \quad \forall p, t \quad (9)$$

$$\sum_{r \in R_a} Y_{a,d,p_a,r} \leq wub_a \quad \forall a, d \mid d \in D_a \quad (10)$$

$$\sum_{r \in R_a} Y_{a,d,p_a,r} \leq wub_a \sum_t W_{d,p_a,t}^T \quad \forall a, d \mid a \in A^T, d \in D_a \quad (11)$$

$$O_a \geq \frac{U_{a,d_a^{Last},p_a} - \sum_{r \in R_a} Y_{a,d_a^{Last},p_a,r}}{wd_a} \quad \forall a \quad (12)$$

$$\sum_r TP_{d,p,r} \leq \sum_t beds_t W_{d,p,t}^T \quad \forall d, p \quad (13)$$

$$\sum_r TP_{d,p,r} \leq \sum_r W_{d,p,r} \quad \forall d, p \quad (14)$$

$$\sum_r X_{d,flight,p,p',r} = 0 \quad \forall d, p, p' \mid d \notin D_{p,p'} \quad (15)$$

$$W_{d,p,r}, X_{d,m,p,p',r}, TP_{d,p,r} \in \{0,1,2,3,\dots\} \quad \forall d, m, p, p', r \quad (16)$$

$$U_{a,d,p_a}, Y_{a,d,p_a,r} \geq 0 \quad \forall a, d, r \quad (17)$$

$$W_{d,p,t}^T, X_{d,p,p',t}^T, O_a \in \{0,1\} \quad \forall a, d, p, p', t \quad (18)$$

The objective function (1) seeks to minimize the total penalty points associated with conducting submarine maintenance. We account for the daily penalties for delayed maintenance (during the maintenance window), a one-time penalty for unmet maintenance (after the due date), the transportation penalties for each time we move maintenance tenders and maintenance personnel between ports, and the daily penalties of keeping these tenders and maintenance personnel at each port. The constraint equations serve the following purposes: Equation (2) ensures balance of flow for maintenance

personnel, accounting for travel time; equation (3) ensures the same for tenders; equation (4) ensures required resources are available at each port in order to perform maintenance at that port; equation (5) ensures delayed maintenance is accounted for starting on day d_a^{First} for each task a ; equation (6) ensures delayed maintenance from one day is carried to the following day; equation (7) ensures that maintenance personnel cannot travel by tender if no tender travel occurs; travel and initial location restrictions for day one for maintenance personnel and tenders are given by equations (8) and (9), respectively; equation (10) ensures the number of workers assigned to a given task does not exceed the daily maximum; equation (11) ensures that any maintenance requiring a tender is not conducted unless a tender is present; equation (12) ensures that the overtime control variable equals one if any work is left undone after day d_a^{Last} for maintenance task a ; equation (13) ensures that the number of personnel assigned to the tenders does not exceed its capacity; and equation (14) ensures that the number of personnel assigned to the tenders does not exceed the number of workers currently at the tender's port; equation (15) ensures no flight travel occurs between ports p to p' on days where such travel is not possible; equations (16) - (18) establish variable domains.

3. RSOM Specifications

The input to PSOM is based upon estimates of planned maintenance to be conducted during the planning horizon. We develop RSOM in order to accommodate unanticipated changes to the input data such as sudden repair jobs. RSOM seeks to minimize change to the existing schedule each time there is a significant change to the maintenance demand input of the model (either PSOM or the latest iteration of RSOM).

Changes to the maintenance needs can occur in different ways. The most significant example is a voyage repair mission. In this case, a sudden high-priority maintenance demand can appear hundreds of miles away and require a quick response. Next, the estimated amount of work required for a task is initially estimated based on the information sent from the submarine to the tender. Once the maintenance workers have physically examined the problem, they may determine a job requires a different amount

of work. Also, as time progresses and the planning horizon is extended, new tasks (planned or not) can be added.

A change in maintenance plans is costly. For example, travel by tender requires considerable effort preparing both the tender and its crew for departure. A sudden change to either put a tender underway or to cancel a deployment incurs a cost in time, manpower, and money. Similarly, to suddenly deploy a customized group of maintenance personnel as a FAT incurs high costs. Further, these changes result in workers operating under a less-predictable work schedule. As such, these changes should be carefully determined in a way that minimizes deviation from the existing plan. RSOM seeks to minimize changes to the existing legacy plan using the idea of optimization with persistence [32], described in Section A of this chapter.

4. RSOM Formulation

RSOM uses the following additional parameters and decision variables:

\hat{d} : the last day before rescheduling is allowed [day]

$\hat{X}_{d,m,p,p',r}, \hat{Y}_{a,d,p,r}, \hat{X}_{d,p,p',t}^T$: existing solution values for (variables) $X_{d,m,p,p',r}$, $Y_{a,d,p,r}$, and $X_{d,p,p',t}^T$, respectively, defined in PSOM.

pen^X, pen^{X^T}, pen^Y : penalty points associated with changes in travel for maintenance personnel, travel for tenders, and work scheduled to be complete, respectively. [penalty units/change]

$X_{d,m,p,p',r}^+, X_{d,m,p,p',r}^-$ increase or decrease in travel from the existing plan for personnel type r travelling from port p to port p' by method m on day d , respectively. [workers]

$Y_{a,d,p,r}^+, Y_{a,d,p,r}^-$ increase or decrease in work performed on task a from the existing plan for personnel type r at port p on day d , respectively. [workers]

$X_{d,p,p',t}^{T+}, X_{d,p,p',t}^{T-}$ increase or decrease in travel requirements from the existing plan for tender t travelling from port p to port p' on day d , respectively.

The formulation of RSOM is as follows:

$$\begin{aligned}
\min_{\substack{O, TP, U, W, W^T, X, X^T, Y, \\ Y^+, Y^-, X^+, X^-, X^{T+}, X^{T-}}} & \sum_a c_a^M U_{a,d,p_a} + \sum_a c_a^{Last} O_a + \sum_{d,m,p,p',r} c_{m,p,p'}^T X_{d,m,p,p',r} + \sum_{d,p,r} c_p^D W_{d,p,r} \\
& - \sum_{d,p,r} c_p^{Diff} TP_{d,p,r} + \sum_{d,p,p',t} c_{tender}^T X_{d,p,p',t}^T + \sum_{d,p,t} c_{tender}^D W_{d,p,t}^T \\
& + \sum_{d,m,p,p',r|d>\hat{d}} pen^X (X_{d,m,p,p',r}^+ + X_{d,m,p,p',r}^-) + \sum_{a,d,r|d \in D_a, d>\hat{d}, r \in R_a} pen^Y (Y_{a,d,p_a,r}^+ + Y_{a,d,p_a,r}^-) \\
& + \sum_{d,p,p',t|d>\hat{d}} pen^{X^T} (X_{d,p,p',t}^{T+} + X_{d,p,p',t}^{T-})
\end{aligned} \tag{19}$$

Subject to constraints to (2) through (18), and:

$$X_{d,p,p',t}^T = \hat{X}_{d,p,p',t}^T + X_{d,p,p',t}^{T+} - X_{d,p,p',t}^{T-} \quad \forall d, p, p', t \mid p \neq p', d > \hat{d} \tag{20}$$

$$X_{d,p,p',t}^T = \hat{X}_{d,p,p',t}^T \quad \forall d, p, p', t \mid p \neq p', d \leq \hat{d} \tag{21}$$

$$X_{d,m,p,p',r} = \hat{X}_{d,m,p,p',r} + X_{d,m,p,p',r}^- - X_{d,m,p,p',r}^+ \quad \forall d, m, p, p', r \mid p \neq p', d > \hat{d} \tag{22}$$

$$X_{d,m,p,p',r} = \hat{X}_{d,m,p,p',r} \quad \forall d, m, p, p', r \mid p \neq p', d \leq \hat{d} \tag{23}$$

$$Y_{a,d,p_a,r} = \hat{Y}_{a,d,p_a,r} + Y_{a,d,p_a,r}^+ - Y_{a,d,p_a,r}^- \quad \forall a, d, r \mid d \in D_a, d > \hat{d}, r \in R_a \tag{24}$$

$$Y_{a,d,p_a,r} = \hat{Y}_{a,d,p_a,r} \quad \forall a, d, r \mid d \in D_a, d \leq \hat{d}, r \in R_a \tag{25}$$

$$X_{d,m,p,p',r}^+, X_{d,m,p,p',r}^- \in \{0, 1, 2, 3, \dots\} \quad \forall d, m, p, p', r \tag{26}$$

$$Y_{a,d,p_a,r}^+, Y_{a,d,p_a,r}^- \geq 0 \quad \forall a, d, r \tag{27}$$

$$X_{d,p,p',t}^{T+}, X_{d,p,p',t}^{T-} \in \{0, 1\} \quad \forall d, p, p', t \tag{28}$$

The objective function for RSOM in equation (19), is the same as that of PSOM, except that we also penalize changes to the existing plan. In order to account for changes in the tender movement plan after day \hat{d} and prevent changes before day $\hat{d}+1$ we use equations (20) and (21). Equations (22) and (23) do the same for personnel movement, and equations (24) and (25) do the same for the maintenance work plan. The domains of RSOM's added variables are expressed in equations (26) - (28).

III. MODEL ILLUSTRATION

A. SMALL-SCALE EXAMPLE

1. Description

To illustrate the use of PSOM and RSOM we build a small-size, notional scenario that we refer to as “Scenario 1.” Here the planning horizon is thirty-five days, we consider only four locations for maintenance (Guam, Diego Garcia, Singapore, and Bahrain), and use only three types of maintenance workers (electricians, nuclear workers, and mechanics).

Using a constant tender speed of twenty knots and known distances between ports [36], Table 1 shows the number of days required for a tender to travel between these locations. Similarly, travel times for FATs between locations are shown in Table 2. The distance between Diego Garcia to all other ports and Bahrain to Guam increases the flight travel time. As a result, the flights between these locations will take three days (including time for the maintenance personnel to prepare for travel and maintenance). Flights between Guam and Singapore, and Singapore and Bahrain take only two days. Further, we assume that transportation to or from Diego Garcia is restricted because this location does not receive daily flights. Specifically, in Scenario 1 we do not allow personnel to arrive or depart from Diego Garcia by flight every fourth day, beginning with the first day.

Each maintenance worker in a FAT is assumed to cost thirty penalty points, and five penalty points if travelling by tender. The penalty points incurred for each time a tender travels between any given locations are listed in Table 3. These are calculated proportionally to the number of days required to complete the trip. Table 4 shows the daily penalty points associated with tenders and personnel in each location. The last column illustrates the reduction in cost for maintenance personnel when they are collocated with a tender.

	Guam	Diego Garcia	Singapore	Bahrain
Guam	0	10	6	13
Diego Garcia	10	0	5	6
Singapore	6	5	0	8
Bahrain	13	6	8	0

Table 1. Scenario 1: Tender travel time between ports, $travel_{tender,p,p'}$ [days]

	Guam	Diego Garcia	Singapore	Bahrain
Guam	0	3	2	3
Diego Garcia	3	0	3	3
Singapore	2	3	0	2
Bahrain	3	3	2	0

Table 2. Scenario 1: FAT travel time between ports, $travel_{flight,p,p'}$ [days]

	Guam	Diego Garcia	Singapore	Bahrain
Guam	0	200	120	260
Diego Garcia	200	0	100	160
Singapore	120	100	0	120
Bahrain	260	120	160	0

Table 3. Scenario 1: Cost for a tender to travel between ports, $c_tender_{p,p'}^T$ [penalty units]

	Daily Cost at each location for each		
	Tender	Maintenance Personnel	Difference for Maintenance Personnel with a Tender
Guam	5	0.5	0.5
Diego Garcia	10	0.5	0.5
Singapore	25	2	1
Bahrain	25	2	1

Table 4. Scenario 1: Daily cost at each location, $c_tender_p^D$, c_p^D , c_p^{DDiff} , respectively [penalty units per tender or worker, as applicable]

There are twenty-two maintenance tasks shown in Table 5 where the columns list most of their characteristics.

	Location	Maintenance Availability		Worker-Days Required	Daily Maximum Number of Workers	Tender Required?	Can be Performed by		
		First Day	Last Day				Mechanical	Nuclear	Electrical
Task 1	Guam	1	12	37	8	Yes	No	Yes	No
Task 2	Guam	1	12	32	10	No	No	No	Yes
Task 3	Guam	1	12	43	14	No	Yes	No	No
Task 4	Diego Garcia	1	10	31	11	No	Yes	Yes	No
Task 5	Diego Garcia	1	10	42	13	No	No	No	Yes
Task 6	Guam	4	15	38	12	No	Yes	No	No
Task 7	Guam	4	15	35	10	No	Yes	Yes	No
Task 8	Singapore	6	15	23	10	Yes	No	Yes	No
Task 9	Singapore	6	15	42	12	No	Yes	No	Yes
Task 10	Guam	13	20	35	12	No	Yes	No	Yes
Task 11	Guam	13	20	45	13	No	Yes	No	Yes
Task 12	Diego Garcia	15	22	46	11	No	Yes	No	No
Task 13	Diego Garcia	15	22	48	7	No	Yes	No	Yes
Task 14	Guam	22	32	32	8	No	No	No	Yes
Task 15	Guam	22	32	40	7	No	No	Yes	Yes
Task 16	Diego Garcia	23	32	28	8	Yes	No	Yes	No
Task 17	Diego Garcia	23	32	38	9	No	Yes	No	No
Task 18	Guam	26	34	33	6	No	Yes	No	No
Task 19	Guam	26	34	48	10	No	Yes	Yes	No
Task 20	Guam	26	34	38	11	Yes	No	Yes	No
Task 21	Diego Garcia	29	34	25	7	No	No	No	Yes
Task 22	Diego Garcia	29	34	20	10	Yes	No	Yes	No

Table 5. Scenario 1: Original maintenance demand and task characteristics

We assume space available aboard tenders, $beds_t$, is 272 for the USS Frank Cable, and 254 for the USS Emory S. Land. These values assume that each of the tenders is capable of housing their original crew size prior to transferring to MSC. We obtain these values as the difference between their original crew size and their hybrid crews.

Initial conditions are as follows: Tenders are located at Guam and Diego Garcia, respectively; there are eight electrical, twelve mechanical, and ten nuclear workers located at Guam; Diego Garcia is manned with four of each type of worker; and the other two locations have none.

For added simplicity, we assume all tasks incur one penalty point for each worker-day of delayed maintenance within the maintenance availability window and a one-time penalty of one-hundred points if unable to complete the task within that window.

2. Analysis of Results

We use PSOM to obtain the optimal solution for this scenario. Every task is complete in time. A full solution output is shown in the Appendix. In this section we briefly highlight some aspects to illustrate the breakdown of penalty points, an example of allocating workers to a task, and the travel plan.

The optimal solution incurs 3,267 penalty points. 2,138 of these points (approximately sixty-five percent) are from delayed maintenance. 485 (fifteen percent) are incurred as a result of tender and personnel travel. The remaining 644 (twenty percent) are the result of the daily costs for personnel and tenders at ports.

The output report includes allocation of personnel to tasks. For example, consider maintenance “Task 10,” illustrated in Figure 2. Two maintenance workers, electrical and mechanical, are capable of conducting work on this task. PSOM schedules a single mechanic for the first two days it is available due to competing maintenance demands with Task 11 (not shown). Thus, most maintenance on this task is delayed. On day fifteen, six additional mechanics start to work on Task 10 and an additional mechanic also switches to Task 10 on day sixteen. These eight mechanics work through day eighteen, and on this day two additional electricians help complete the task.

PSOM schedules tender and personnel travel to complete the maintenance for Scenario 1. On day one, one mechanical and three nuclear workers depart from Diego Garcia for Singapore by tender. To augment these four workers, four mechanical and two electrical workers depart from Guam to Singapore on day four. This travel schedule is in anticipation of Task 8 and Task 9 which start at Singapore on day six. Further, on day five, an additional nuclear worker flies from Guam to Singapore. All maintenance work at Singapore is complete on day eleven. On day twelve, all of the workers there depart Singapore by tender to travel to Diego Garcia.

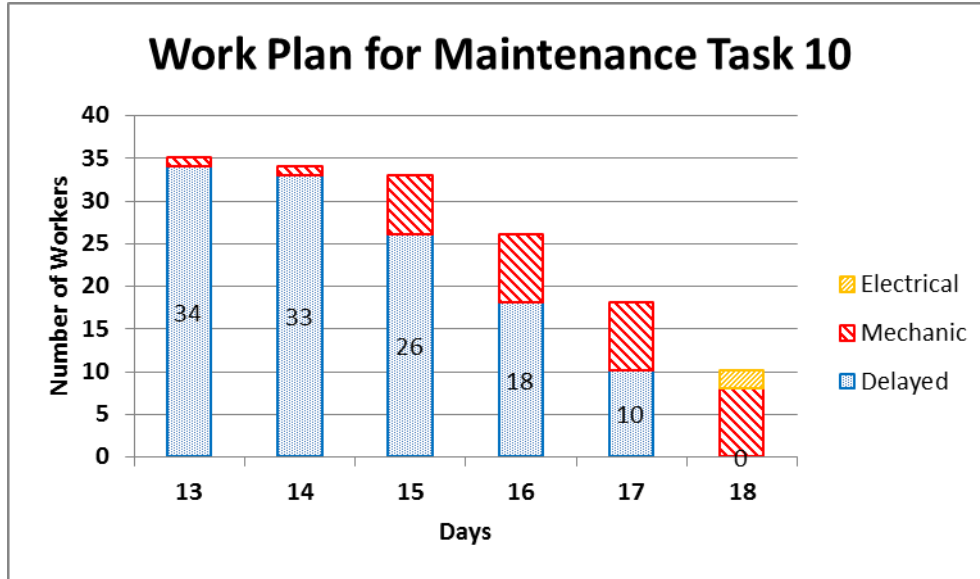


Figure 2. Scenario 1: Allocation of maintenance personnel for Task 10

3. Schedule Change: Voyage Repair Mission

We introduce a change to the input data: On day nine, we receive a voyage repair mission at Bahrain. Its characteristics are shown in Table 6. Each of these tasks incur three penalty points for each worker-day of delayed maintenance and two-hundred penalty points if unable to complete the task within the available maintenance window.

	Location	Maintenance Availability		Worker-Days Required	Daily Maximum Number of Workers	Tender Required?	Can be Performed by		
		First Day	Last Day				Mechanical	Nuclear	Electrical
Task 23	Bahrain	16	28	35	13	No	No	Yes	Yes
Task 24	Bahrain	16	28	20	10	Yes	No	Yes	No
Task 25	Bahrain	16	28	28	10	No	Yes	Yes	No

Table 6. Scenario 1: Voyage repair maintenance demand and task characteristics

We use the solution from PSOM in the previous section as the existing plan, and run RSOM to accommodate the new demand. RSOM charges two penalty points for each change in personnel travel, ten penalty points for changes to tender travel, and one point for each worker per day of change to the existing maintenance plan.

With the stress of the added maintenance demand at Bahrain, the travel plan becomes more complicated after day nine. Instead of sending all of the workers from Singapore to Diego Garcia via tender on day twelve, RSOM schedules only four

mechanics to travel from Singapore to Diego Garcia by flight, and the tender departs Singapore for Bahrain carrying no workers from Singapore. On day twelve one nuclear worker also flies from Diego Garcia to Bahrain. This worker will arrive one day prior to when work begins there, but he or she has been scheduled to depart early due to the lack of flights departing from Diego Garcia to Bahrain on day thirteen. On day thirteen, six more nuclear workers depart from Guam to Bahrain by flight. On day fourteen, seven workers (four nuclear, two electrical, and one mechanical) depart from Singapore to Bahrain by flight. These workers become available for work at Bahrain on day sixteen, the day the maintenance demand starts. On day twenty, one nuclear worker departs by flight from Bahrain to Diego Garcia. The tender, travelling from Singapore, arrives on day twenty and must be present for the work on Task 24. There are a sufficient number of maintenance workers at Bahrain to complete that task in two days which allows the tender to depart for Diego Garcia on day twenty-two with seven nuclear and two electrical workers in order to meet the demands of Task 16. Also on day twenty-two, three nuclear workers depart from Bahrain to Guam by flight. A single mechanic stays at Bahrain to complete the work there and departs on day twenty three by flight for Guam.

To see an example of the differences in work scheduling, we examine maintenance Task 19. Figure 3 shows the PSOM existing solution in which over half of the work is conducted by nuclear workers and 109 penalty points are accrued for delayed maintenance. In the existing solution there are eight mechanical and nine nuclear workers at Guam at the time of this maintenance. However, in the RSOM solution there are nine mechanical and seven nuclear workers at Guam during this maintenance. The modified work plan for task nineteen is shown in Figure 4. In this solution just over a third of the work on this task is conducted by the nuclear workers and this task incurs 120 penalty points for delayed maintenance.

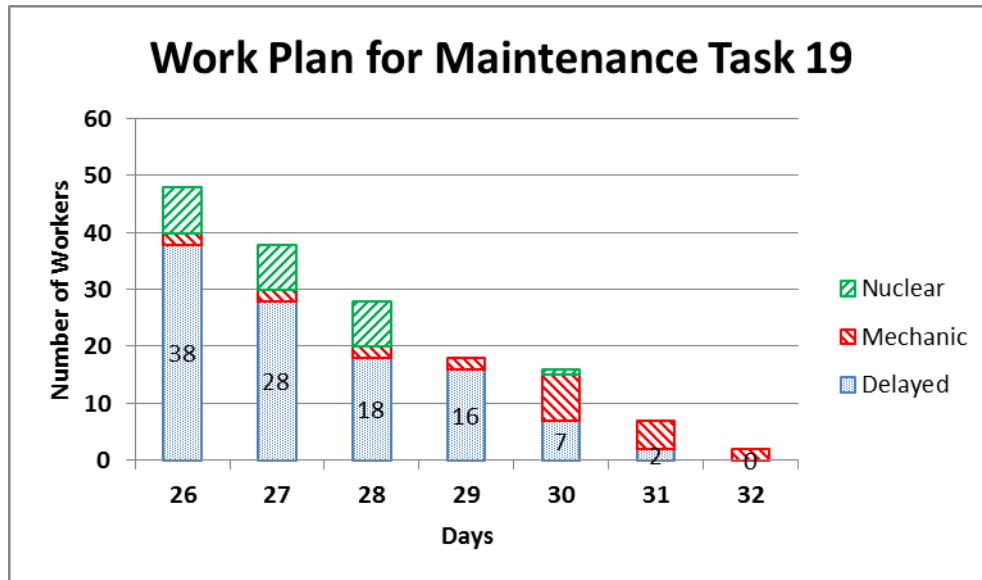


Figure 3. Scenario 1: Existing (PSOM) maintenance plan for Task 19

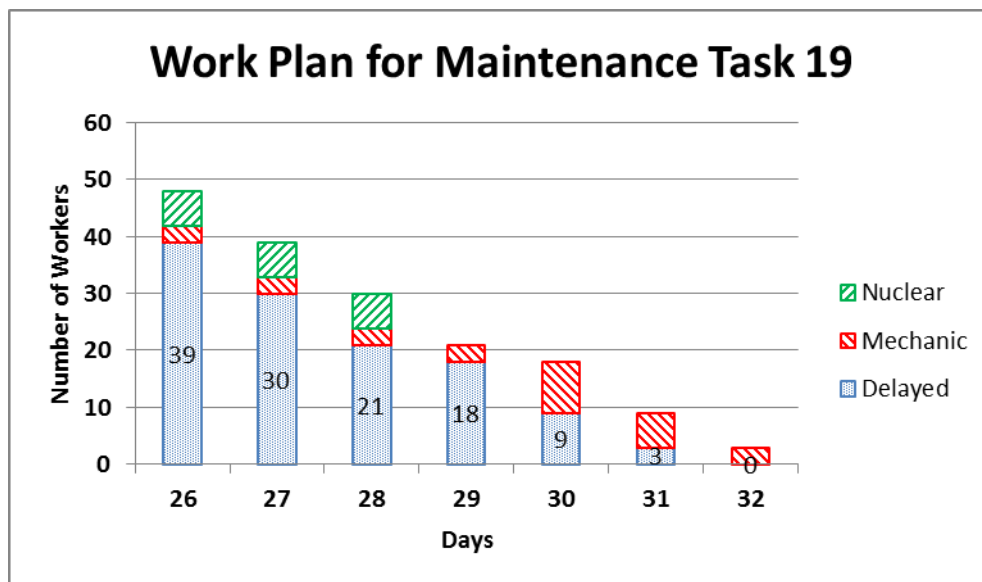


Figure 4. Scenario 1: Modified (RSOM) maintenance plan for Task 19

The result produced by RSOM incurs 5,487 penalty points. Delayed maintenance penalties increase by sixty-eight percent (to 3,296 points) with respect to the case without the voyage repair. Transportation costs also increase by 169 percent (to 1,305 points), and the total daily costs increase by twenty-seven percent (to 816 points). The penalties for changes to the existing plan are: eighty-six points for changes in personnel travel,

thirty points for changes in tender travel, and 224 points for changes to work. Similar to the results for PSOM, every task is complete within the time allotted.

B. LARGE-SCALE EXAMPLE: COMPUTATIONAL DETAILS

PSOM and RSOM have been implemented in the General Algebraic Modeling System [37] software using CPLEX [38] as the solve engine. All tests are conducted on a computer running under Windows 7 with two 3.0-GHz processors and ninety-six GB of memory.

For Scenario 1, we can produce an optimal solution for PSOM in fifteen seconds and for RSOM in less than five seconds.

We also have created a larger example, called Scenario 2, to test our models on a realistically-sized PSOM. Scenario 2 uses eleven ports, 152 workers from ten worker types, sixty maintenance tasks, and parameter inputs similar to Scenario 1 over a planning horizon of forty days. The associated PSOM has 208,359 variables (of which just over fifty percent are discrete variables) and 16,450 constraints. During the pre-solve phase, CPLEX eliminates constraints and variables, reducing the model size to 93,831 variables (of which 8,331 are binaries) and 11,562 constraints. This PSOM example is solved within ten percent of optimality in eleven hours. Next, we create a voyage repair (similar to Scenario 1), and the associated RSOM is solved optimally in fifteen minutes.

IV. CONCLUSIONS

In this thesis, we have developed two mixed-integer, linear optimization models, PSOM and RSOM, which can guide planners on the resourcing of U.S. Navy submarine maintenance conducted by the tenders in the Fifth and Seventh Fleets. Assuming demand for maintenance tasks is known, PSOM schedules (a) workers to tasks, and (b) personnel travel (as a FAT or by tender), over time. The schedule minimizes penalties for delayed and/or incomplete work, personnel travel, and personnel dwelling with or without a tender. A second model, RSOM, can be used to accommodate emergent, unscheduled demands by producing an updated schedule that minimizes the impact of needed changes on the existing schedule. We have demonstrated these complementary models using a small, fictitious scenario. We have also used a larger, notional scenario to demonstrate the computational feasibility of the approach.

PSOM and RSOM can be improved in several areas, as outlined next:

- Both models should be exercised with real data to validate the approach. This will allow us to determine key features that need to be modified from or added to the model specifications.
- Penalties for delayed and incomplete work are subjective (i.e., they do not correspond with direct dollar costs). While the flexibility in setting those penalties may allow planners to produce different courses of action, it also lends itself to (possibly unconscious) manipulation to seek an anticipated output. Additional constraints (e.g., limiting the total delayed or incomplete work) could replace subjective penalties.
- Both models can be enhanced by better accounting for precedence relationships among tasks. Currently, neither model has visibility of task precedence except via availability windows: if Task 1 is a predecessor for Task 2, planners must input those windows without overlapping. However, this prevents feasible options where, for example, if Task 1 is scheduled to be completed early, Task 2 should also be allowed to begin early.
- A final improvement for RSOM is to incorporate decision variables for the movement of submarines with unscheduled demands. The resulting model would determine the optimal location for the maintenance resources and submarines to meet.

More broadly, optimization and simulation can be employed to answer the overarching question about tender and submarine homeports.

Finally, during conversations with planning personnel, it has been pointed out the usefulness of a full job-shop model capability for each of the tenders individually considered. Developing such capability would greatly enhance the current maintenance planning process, which is only aided by Microsoft Project Scheduler [39].

APPENDIX

Below is the full PSOM solution output for Scenario 1, organized by category.

Summary Output

```
Objective Function Value is  3267.0

Objective Function Breakdown:
Cost of delayed maintenance: 2138.0
Cost of transporting personnel:  285.0
Total cost for personnel at all locations:  788.0
Total savings for personnel collocated with a tender:  659.0
Tender movement costs:  200.0
Total cost for tenders at all locations:  515.0
Cost of unmet maintenance:    0.0
```

Schedule by day and location

Day	Port	Task	Complete	Delayed	Number of Workers Allocated by Type	
Day 1						
	GUAM					
		Task1	8	29	8 Nuclear	
		Task2	8	24	8 Electric	
		Task3	12	31	12 Mechanic	
	DG					
		Task4	4	27	3 Mechanic	1 Nuclear
		Task5	4	38	4 Electric	
	SINGAPORE					
	BAHRAIN					
Day 2						
	GUAM					

Day 3	DG	Task1	8	21	8 Nuclear	
		Task2	8	16	8 Electric	
		Task3	12	19	12 Mechanic	
		Task4	4	23	3 Mechanic	1 Nuclear
		Task5	4	34	4 Electric	
	SINGAPORE					
	BAHRAIN					
	GUAM					
	DG	Task1	8	13	8 Nuclear	
		Task2	8	8	8 Electric	
Task3		12	7	12 Mechanic		
Task4		4	19	3 Mechanic	1 Nuclear	
Task5		4	30	4 Electric		
SINGAPORE						
BAHRAIN						
Day 4	GUAM	Task1	0	13		
		Task2	6	2	6 Electric	
		Task3	7	0	7 Mechanic	
		Task6	1	37	1 Mechanic	
		Task7	10	25	10 Nuclear	
	DG	Task4	4	15	3 Mechanic	1 Nuclear
		Task5	4	26	4 Electric	
		SINGAPORE				
	BAHRAIN					
	Day 5					

Day 6	GUAM		Task1	0	13		
			Task2	2	0	2 Electric	
			Task6	8	29	8 Mechanic	
			Task7	9	16	9 Nuclear	
	DG		Task4	4	11	3 Mechanic	1 Nuclear
			Task5	4	22	4 Electric	
	SINGAPORE						
	BAHRAIN						
	GUAM		Task1	0	13		
			Task6	8	21	8 Mechanic	
			Task7	9	7	9 Nuclear	
	DG		Task4	4	7	3 Mechanic	1 Nuclear
			Task5	4	18	4 Electric	
	SINGAPORE		Task8	3	20	3 Nuclear	
			Task9	7	35	2 Electric	5 Mechanic
	BAHRAIN						
Day 7	GUAM		Task1	3	10	3 Nuclear	
			Task6	8	13	8 Mechanic	
			Task7	6	1	6 Nuclear	
	DG		Task4	4	3	3 Mechanic	1 Nuclear
			Task5	4	14	4 Electric	
	SINGAPORE		Task8	4	16	4 Nuclear	

Day 8	BAHRAIN	Task9	7	28	2 Electric	5 Mechanic
	GUAM	Task1	8	2	8 Nuclear	
		Task6	8	5	8 Mechanic	
		Task7	1	0	1 Nuclear	
	DG	Task4	3	0	3 Mechanic	
		Task5	4	10	4 Electric	
	SINGAPORE	Task8	4	12	4 Nuclear	
		Task9	7	21	2 Electric	5 Mechanic
	BAHRAIN					
Day 9	GUAM	Task1	2	0	2 Nuclear	
		Task6	5	0	5 Mechanic	
	DG	Task5	4	6	4 Electric	
		Task8	4	8	4 Nuclear	
	SINGAPORE	Task9	7	14	2 Electric	5 Mechanic
	BAHRAIN					
Day 10	GUAM					
	DG					
		Task5	4	2	4 Electric	
	SINGAPORE	Task8	4	4	4 Nuclear	
		Task9	7	7	2 Electric	5 Mechanic

Day 11	BAHRAIN						
	GUAM						
	DG						
	SINGAPORE						
	Task8	4	0	4 Nuclear			
Day 12	Task9	7	0	2 Electric	5 Mechanic		
	BAHRAIN						
	GUAM						
	DG						
	SINGAPORE						
Day 13	BAHRAIN						
	GUAM						
	Task10	1	34	1 Mechanic			
	Task11	13	32	6 Electric	7 Mechanic		
	DG						
Day 14	SINGAPORE						
	BAHRAIN						
	GUAM						
	Task10	1	33	1 Mechanic			
	Task11	13	19	6 Electric	7 Mechanic		
Day 15	DG						
	SINGAPORE						
	BAHRAIN						
	GUAM						

Day 16	DG	Task10	7	26	7 Mechanic	
		Task11	7	12	6 Electric	1 Mechanic
		Task12	0	46		
		Task13	7	41	4 Electric	3 Mechanic
	SINGAPORE BAHRAIN					
	GUAM					
	DG	Task10	8	18	8 Mechanic	
		Task11	6	6	6 Electric	
		Task12	0	46		
		Task13	7	34	4 Electric	3 Mechanic
	SINGAPORE BAHRAIN					
Day 17	GUAM					
	DG	Task10	8	10	8 Mechanic	
		Task11	6	0	6 Electric	
		Task12	7	39	7 Mechanic	
		Task13	7	27	6 Electric	1 Mechanic
	SINGAPORE BAHRAIN					
Day 18	GUAM					
	DG	Task10	10	0	2 Electric	8 Mechanic
		Task12	7	32	7 Mechanic	
		Task13	7	20	6 Electric	1 Mechanic

Day 19	SINGAPORE			
	BAHRAIN			
	GUAM			
	DG			
	Task12	8	24	8 Mechanic
Day 20	Task13	6	14	6 Electric
	SINGAPORE			
	BAHRAIN			
	GUAM			
	DG			
Day 21	Task12	8	16	8 Mechanic
	Task13	6	8	6 Electric
	SINGAPORE			
	BAHRAIN			
	GUAM			
Day 22	DG			
	Task12	8	8	8 Mechanic
	Task13	6	2	6 Electric
	SINGAPORE			
	BAHRAIN			
Day 22	GUAM			
	Task14	6	26	6 Electric
	Task15	7	33	7 Nuclear
	DG			
	Task12	8	0	8 Mechanic
	Task13	2	0	2 Electric

Day 23	SINGAPORE				
	BAHRAIN				
	GUAM				
	Task14	6	20	6 Electric	
	Task15	7	26	7 Nuclear	
	DG				
	Task16	5	23	5 Nuclear	
	Task17	8	30	8 Mechanic	
	SINGAPORE				
	BAHRAIN				
Day 24	GUAM				
	Task14	6	14	6 Electric	
	Task15	7	19	7 Nuclear	
	DG				
	Task16	5	18	5 Nuclear	
	Task17	8	22	8 Mechanic	
	SINGAPORE				
	BAHRAIN				
	SINGAPORE				
	BAHRAIN				
Day 25	GUAM				
	Task14	6	8	6 Electric	
	Task15	7	12	7 Nuclear	
	DG				
	Task16	5	13	5 Nuclear	
	Task17	8	14	8 Mechanic	
	SINGAPORE				
	BAHRAIN				
	SINGAPORE				
	BAHRAIN				
Day 26					

Day 27	GUAM					
	Task14	0	8			
	Task15	6	6	6 Electric		
	Task18	6	27	6 Mechanic		
	Task19	10	38	2 Mechanic	8 Nuclear	
	Task20	1	37	1 Nuclear		
	DG					
	Task16	5	8	5 Nuclear		
	Task17	8	6	8 Mechanic		
	SINGAPORE					
	BAHRAIN					
	GUAM					
	Task14	0	8			
	Task15	6	0	6 Electric		
	Task18	6	21	6 Mechanic		
	Task19	10	28	2 Mechanic	8 Nuclear	
	Task20	1	36	1 Nuclear		
	DG					
	Task16	5	3	5 Nuclear		
	Task17	6	0	6 Mechanic		
	SINGAPORE					
	BAHRAIN					
Day 28	GUAM					
	Task14	6	2	6 Electric		
	Task18	6	15	6 Mechanic		
	Task19	10	18	2 Mechanic	8 Nuclear	
	Task20	1	35	1 Nuclear		
	DG					
	Task16	3	0	3 Nuclear		
	SINGAPORE					

Day 29	BAHRAIN						
	GUAM	Task14	2	0	2 Electric		
		Task18	6	9	6 Mechanic		
		Task19	2	16	2 Mechanic		
		Task20	9	26	9 Nuclear		
		DG					
		Task21	6	19	6 Electric		
		Task22	5	15	5 Nuclear		
	SINGAPORE						
	BAHRAIN						
Day 30	GUAM	Task18	0	9			
		Task19	9	7	8 Mechanic	1 Nuclear	
		Task20	8	18	8 Nuclear		
		DG					
		Task21	6	13	6 Electric		
		Task22	5	10	5 Nuclear		
	SINGAPORE						
	BAHRAIN						
	Day 31	GUAM	Task18	3	6	3 Mechanic	
			Task19	5	2	5 Mechanic	
Task20			9	9	9 Nuclear		
DG		Task21	6	7	6 Electric		
		Task22	5	5	5 Nuclear		
SINGAPORE							

Day 32	BAHRAIN				
	GUAM				
	Task18	6	0	6	Mechanic
	Task19	2	0	2	Mechanic
	Task20	9	0	9	Nuclear
	DG				
	Task21	6	1	6	Electric
	Task22	5	0	5	Nuclear
	SINGAPORE				
	BAHRAIN				
Day 33	GUAM				
	DG				
	Task21	1	0	1	Electric
	SINGAPORE				
	BAHRAIN				
Day 34	GUAM				
	DG				
	SINGAPORE				
	BAHRAIN				
Day 35	GUAM				
	DG				
	SINGAPORE				
	BAHRAIN				

Unmet tasks

None

Travel by worker type and day

Electrical workers' travel:

Day 1	8 worker(s) waits at GUAM	
Day 1	4 worker(s) waits at DG	
Day 2	8 worker(s) waits at GUAM	
Day 2	4 worker(s) waits at DG	
Day 3	8 worker(s) waits at GUAM	
Day 3	4 worker(s) waits at DG	
Day 4	6 worker(s) waits at GUAM	
Day 4	2 worker(s) travels from GUAM	to SINGAPORE by flight
Day 4	4 worker(s) waits at DG	
Day 5	6 worker(s) waits at GUAM	
Day 5	4 worker(s) waits at DG	
Day 6	6 worker(s) waits at GUAM	
Day 6	4 worker(s) waits at DG	
Day 6	2 worker(s) waits at SINGAPORE	
Day 7	6 worker(s) waits at GUAM	
Day 7	4 worker(s) waits at DG	
Day 7	2 worker(s) waits at SINGAPORE	
Day 8	6 worker(s) waits at GUAM	
Day 8	4 worker(s) waits at DG	
Day 8	2 worker(s) waits at SINGAPORE	
Day 9	6 worker(s) waits at GUAM	
Day 9	4 worker(s) waits at DG	
Day 9	2 worker(s) waits at SINGAPORE	
Day 10	6 worker(s) waits at GUAM	
Day 10	4 worker(s) waits at DG	
Day 10	2 worker(s) waits at SINGAPORE	
Day 11	6 worker(s) waits at GUAM	
Day 11	4 worker(s) waits at DG	
Day 11	2 worker(s) waits at SINGAPORE	
Day 12	6 worker(s) waits at GUAM	
Day 12	4 worker(s) waits at DG	
Day 12	2 worker(s) travels from SINGAPORE to DG	by tender

Day 13	6 worker(s) waits at GUAM
Day 13	4 worker(s) waits at DG
Day 14	6 worker(s) waits at GUAM
Day 14	4 worker(s) waits at DG
Day 15	6 worker(s) waits at GUAM
Day 15	4 worker(s) waits at DG
Day 16	6 worker(s) waits at GUAM
Day 16	4 worker(s) waits at DG
Day 17	6 worker(s) waits at GUAM
Day 17	6 worker(s) waits at DG
Day 18	6 worker(s) waits at GUAM
Day 18	6 worker(s) waits at DG
Day 19	6 worker(s) waits at GUAM
Day 19	6 worker(s) waits at DG
Day 20	6 worker(s) waits at GUAM
Day 20	6 worker(s) waits at DG
Day 21	6 worker(s) waits at GUAM
Day 21	6 worker(s) waits at DG
Day 22	6 worker(s) waits at GUAM
Day 22	6 worker(s) waits at DG
Day 23	6 worker(s) waits at GUAM
Day 23	6 worker(s) waits at DG
Day 24	6 worker(s) waits at GUAM
Day 24	6 worker(s) waits at DG
Day 25	6 worker(s) waits at GUAM
Day 25	6 worker(s) waits at DG
Day 26	6 worker(s) waits at GUAM
Day 26	6 worker(s) waits at DG
Day 27	6 worker(s) waits at GUAM
Day 27	6 worker(s) waits at DG
Day 28	6 worker(s) waits at GUAM
Day 28	6 worker(s) waits at DG
Day 29	6 worker(s) waits at GUAM
Day 29	6 worker(s) waits at DG

Day 30	6 worker(s) waits at GUAM
Day 30	6 worker(s) waits at DG
Day 31	6 worker(s) waits at GUAM
Day 31	6 worker(s) waits at DG
Day 32	6 worker(s) waits at GUAM
Day 32	6 worker(s) waits at DG
Day 33	6 worker(s) waits at GUAM
Day 33	6 worker(s) waits at DG
Day 34	6 worker(s) waits at GUAM
Day 34	6 worker(s) waits at DG
Day 35	6 worker(s) waits at GUAM
Day 35	6 worker(s) waits at DG

Mechanical workers' travel:

Day 1	12 worker(s) waits at GUAM	
Day 1	3 worker(s) waits at DG	
Day 1	1 worker(s) travels from DG	to SINGAPORE by tender
Day 2	12 worker(s) waits at GUAM	
Day 2	3 worker(s) waits at DG	
Day 3	12 worker(s) waits at GUAM	
Day 3	3 worker(s) waits at DG	
Day 4	8 worker(s) waits at GUAM	
Day 4	4 worker(s) travels from GUAM	to SINGAPORE by flight
Day 4	3 worker(s) waits at DG	
Day 5	8 worker(s) waits at GUAM	
Day 5	3 worker(s) waits at DG	
Day 6	8 worker(s) waits at GUAM	
Day 6	3 worker(s) waits at DG	
Day 6	5 worker(s) waits at SINGAPORE	
Day 7	8 worker(s) waits at GUAM	
Day 7	3 worker(s) waits at DG	
Day 7	5 worker(s) waits at SINGAPORE	
Day 8	8 worker(s) waits at GUAM	
Day 8	3 worker(s) waits at DG	

Day 8	5 worker(s) waits at SINGAPORE	
Day 9	8 worker(s) waits at GUAM	
Day 9	3 worker(s) waits at DG	
Day 9	5 worker(s) waits at SINGAPORE	
Day 10	8 worker(s) waits at GUAM	
Day 10	3 worker(s) waits at DG	
Day 10	5 worker(s) waits at SINGAPORE	
Day 11	8 worker(s) waits at GUAM	
Day 11	3 worker(s) waits at DG	
Day 11	5 worker(s) waits at SINGAPORE	
Day 12	8 worker(s) waits at GUAM	
Day 12	3 worker(s) waits at DG	
Day 12	5 worker(s) travels from SINGAPORE to DG	by tender
Day 13	8 worker(s) waits at GUAM	
Day 13	3 worker(s) waits at DG	
Day 14	8 worker(s) waits at GUAM	
Day 14	3 worker(s) waits at DG	
Day 15	8 worker(s) waits at GUAM	
Day 15	3 worker(s) waits at DG	
Day 16	8 worker(s) waits at GUAM	
Day 16	3 worker(s) waits at DG	
Day 17	8 worker(s) waits at GUAM	
Day 17	8 worker(s) waits at DG	
Day 18	8 worker(s) waits at GUAM	
Day 18	8 worker(s) waits at DG	
Day 19	8 worker(s) waits at GUAM	
Day 19	8 worker(s) waits at DG	
Day 20	8 worker(s) waits at GUAM	
Day 20	8 worker(s) waits at DG	
Day 21	8 worker(s) waits at GUAM	
Day 21	8 worker(s) waits at DG	
Day 22	8 worker(s) waits at GUAM	
Day 22	8 worker(s) waits at DG	
Day 23	8 worker(s) waits at GUAM	

Day 23	8 worker(s) waits at DG
Day 24	8 worker(s) waits at GUAM
Day 24	8 worker(s) waits at DG
Day 25	8 worker(s) waits at GUAM
Day 25	8 worker(s) waits at DG
Day 26	8 worker(s) waits at GUAM
Day 26	8 worker(s) waits at DG
Day 27	8 worker(s) waits at GUAM
Day 27	8 worker(s) waits at DG
Day 28	8 worker(s) waits at GUAM
Day 28	8 worker(s) waits at DG
Day 29	8 worker(s) waits at GUAM
Day 29	8 worker(s) waits at DG
Day 30	8 worker(s) waits at GUAM
Day 30	8 worker(s) waits at DG
Day 31	8 worker(s) waits at GUAM
Day 31	8 worker(s) waits at DG
Day 32	8 worker(s) waits at GUAM
Day 32	8 worker(s) waits at DG
Day 33	8 worker(s) waits at GUAM
Day 33	8 worker(s) waits at DG
Day 34	8 worker(s) waits at GUAM
Day 34	8 worker(s) waits at DG
Day 35	8 worker(s) waits at GUAM
Day 35	8 worker(s) waits at DG

Nuclear workers' travel:

Day 1	10 worker(s) waits at GUAM	
Day 1	1 worker(s) waits at DG	
Day 1	3 worker(s) travels from DG	to SINGAPORE by tender
Day 2	10 worker(s) waits at GUAM	
Day 2	1 worker(s) waits at DG	
Day 3	10 worker(s) waits at GUAM	
Day 3	1 worker(s) waits at DG	

Day 4	10 worker(s)	waits at GUAM	
Day 4	1 worker(s)	waits at DG	
Day 5	9 worker(s)	waits at GUAM	
Day 5	1 worker(s)	travels from GUAM	to SINGAPORE by flight
Day 5	1 worker(s)	waits at DG	
Day 6	9 worker(s)	waits at GUAM	
Day 6	1 worker(s)	waits at DG	
Day 6	3 worker(s)	waits at SINGAPORE	
Day 7	9 worker(s)	waits at GUAM	
Day 7	1 worker(s)	waits at DG	
Day 7	4 worker(s)	waits at SINGAPORE	
Day 8	9 worker(s)	waits at GUAM	
Day 8	1 worker(s)	waits at DG	
Day 8	4 worker(s)	waits at SINGAPORE	
Day 9	9 worker(s)	waits at GUAM	
Day 9	1 worker(s)	waits at DG	
Day 9	4 worker(s)	waits at SINGAPORE	
Day 10	9 worker(s)	waits at GUAM	
Day 10	1 worker(s)	waits at DG	
Day 10	4 worker(s)	waits at SINGAPORE	
Day 11	9 worker(s)	waits at GUAM	
Day 11	1 worker(s)	waits at DG	
Day 11	4 worker(s)	waits at SINGAPORE	
Day 12	9 worker(s)	waits at GUAM	
Day 12	1 worker(s)	waits at DG	
Day 12	4 worker(s)	travels from SINGAPORE to DG	by tender
Day 13	9 worker(s)	waits at GUAM	
Day 13	1 worker(s)	waits at DG	
Day 14	9 worker(s)	waits at GUAM	
Day 14	1 worker(s)	waits at DG	
Day 15	9 worker(s)	waits at GUAM	
Day 15	1 worker(s)	waits at DG	
Day 16	9 worker(s)	waits at GUAM	
Day 16	1 worker(s)	waits at DG	

Day 17	9 worker(s) waits at GUAM
Day 17	5 worker(s) waits at DG
Day 18	9 worker(s) waits at GUAM
Day 18	5 worker(s) waits at DG
Day 19	9 worker(s) waits at GUAM
Day 19	5 worker(s) waits at DG
Day 20	9 worker(s) waits at GUAM
Day 20	5 worker(s) waits at DG
Day 21	9 worker(s) waits at GUAM
Day 21	5 worker(s) waits at DG
Day 22	9 worker(s) waits at GUAM
Day 22	5 worker(s) waits at DG
Day 23	9 worker(s) waits at GUAM
Day 23	5 worker(s) waits at DG
Day 24	9 worker(s) waits at GUAM
Day 24	5 worker(s) waits at DG
Day 25	9 worker(s) waits at GUAM
Day 25	5 worker(s) waits at DG
Day 26	9 worker(s) waits at GUAM
Day 26	5 worker(s) waits at DG
Day 27	9 worker(s) waits at GUAM
Day 27	5 worker(s) waits at DG
Day 28	9 worker(s) waits at GUAM
Day 28	5 worker(s) waits at DG
Day 29	9 worker(s) waits at GUAM
Day 29	5 worker(s) waits at DG
Day 30	9 worker(s) waits at GUAM
Day 30	5 worker(s) waits at DG
Day 31	9 worker(s) waits at GUAM
Day 31	5 worker(s) waits at DG
Day 32	9 worker(s) waits at GUAM
Day 32	5 worker(s) waits at DG
Day 33	9 worker(s) waits at GUAM
Day 33	5 worker(s) waits at DG

Day 34	9 worker(s) waits at GUAM
Day 34	5 worker(s) waits at DG
Day 35	9 worker(s) waits at GUAM
Day 35	5 worker(s) waits at DG

Tender travel (FCB = USS Frank Cable, ESL = USS Emory S. Land)

Day 1	FCB waits at GUAM	
Day 1	ESL travels from DG	to SINGAPORE
Day 2	FCB waits at GUAM	
Day 3	FCB waits at GUAM	
Day 4	FCB waits at GUAM	
Day 5	FCB waits at GUAM	
Day 6	FCB waits at GUAM	
Day 6	ESL waits at SINGAPORE	
Day 7	FCB waits at GUAM	
Day 7	ESL waits at SINGAPORE	
Day 8	FCB waits at GUAM	
Day 8	ESL waits at SINGAPORE	
Day 9	FCB waits at GUAM	
Day 9	ESL waits at SINGAPORE	
Day 10	FCB waits at GUAM	
Day 10	ESL waits at SINGAPORE	
Day 11	FCB waits at GUAM	
Day 11	ESL waits at SINGAPORE	
Day 12	FCB waits at GUAM	
Day 12	ESL travels from SINGAPORE to DG	
Day 13	FCB waits at GUAM	
Day 14	FCB waits at GUAM	
Day 15	FCB waits at GUAM	
Day 16	FCB waits at GUAM	
Day 17	FCB waits at GUAM	
Day 17	ESL waits at DG	
Day 18	FCB waits at GUAM	
Day 18	ESL waits at DG	

Day 19	FCB waits at GUAM
Day 19	ESL waits at DG
Day 20	FCB waits at GUAM
Day 20	ESL waits at DG
Day 21	FCB waits at GUAM
Day 21	ESL waits at DG
Day 22	FCB waits at GUAM
Day 22	ESL waits at DG
Day 23	FCB waits at GUAM
Day 23	ESL waits at DG
Day 24	FCB waits at GUAM
Day 24	ESL waits at DG
Day 25	FCB waits at GUAM
Day 25	ESL waits at DG
Day 26	FCB waits at GUAM
Day 26	ESL waits at DG
Day 27	FCB waits at GUAM
Day 27	ESL waits at DG
Day 28	FCB waits at GUAM
Day 28	ESL waits at DG
Day 29	FCB waits at GUAM
Day 29	ESL waits at DG
Day 30	FCB waits at GUAM
Day 30	ESL waits at DG
Day 31	FCB waits at GUAM
Day 31	ESL waits at DG
Day 32	FCB waits at GUAM
Day 32	ESL waits at DG
Day 33	FCB waits at GUAM
Day 33	ESL waits at DG
Day 34	FCB waits at GUAM
Day 34	ESL waits at DG
Day 35	FCB waits at GUAM
Day 35	ESL waits at DG

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